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HIGH VOLTAGE BREAKDOWN STUDY

Report No. 7

Seventh Quarterly Progress Report

16 May 1966 through 15 August 1966

Contract DA-28-043-AMC-00394(E)
AMC Task No. 7900.21.243.40.00

November 1966

Prepared for:

U.S. Army Electronics Command
Fort Monmouth, New Jersey

Prepared by:

Ion Physics Corporation
Burlington, Massachusetts

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HIGH VOLTAGE BREAKDOWN STUDY

Report No. 7

Seventh Quarterly Progress Report

16 May 1966 through 15 August 1966

Objective: To determine the factors influencing high voltage vacuum breakdown in conditions consistent with high power tube operation.

Contract DA-28-043-AMC-00394(E)

Technical Guidelines dated 27 March 1964

AMC Task No. 7900.21.243.40.00

This report was prepared by:

A. S. Denholm, M. J. Mulcahy, G. K. Simcox,
M. M. Thayer, A. Watson, and R. White

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Burlington, Massachusetts

DISTRIBUTION STATEMENT

TABLE OF CONTENTS

		Page
PURPOSE		1
ABSTRACT		2
LECTURES, CONFERENCES AND PUBLICATIONS		3
1.	INTRODUCTION	5
	1.1 300 kv System	5
	1.2 Pilot Experiment	5
2.	300 KV TEST VEHICLE	7
	2.1 Vacuum Chamber	7
	2.2 Baking System	7
	2.3 High Voltage Power Supply	7
	2.4 Monitoring and Recording	7
	2.5 Magnetic Field System	8
	2.6 Energy Storage System	8
	2.7 Feedthrough Bushing	8
	2.7.1 General	8
	2.7.2 Bakeable Column	8
	2.7.3 Unbakeable Column	8
	2.8 Dielectric Envelopes	9
	2.9 Electrodes	9
3.	PILOT EXPERIMENT	11
	3.1 Introduction	11
	3.2 Physical Analysis of Results	11
	3.2.1 Procedures	11
	3.2.2 Breakdown Voltage and Prebreakdown Current Data	11
	3.2.3 Pressure Surges	17
	3.3 Theory	17
	3.3.1 Breakdown Mechanism	17
	3.3.2 Field Enhancement	22
	3.3.3 Field Emission Current	23

TABLE OF CONTENTS (Continued)

		Page
3.3.4	The Anode Temperature and Rate of Gas Evolution	24
3.3.5	The Ionic Space Charge Field	25
3.4	Interpretation of Results	29
3.5	Statistical Analysis of Results	33
3.6	Conclusions	36
4.	REFERENCES	37
5.	FUTURE EFFORT	39
6.	IDENTIFICATION OF PERSONNEL	41

LIST OF ILLUSTRATIONS

Figure		Page
1	Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (1) Fresh Electrodes.	12
2	Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (2) after conditioning.	13
3	Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (3) after further conditioning.	14
4	Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (4) after deconditioning.	15
5	Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (5) conditioned after deconditioning.	16
6	Penultimate Gap Current as a Function of Voltage from Figures 1-3.	18
7	Penultimate Gap Current as a Function of Voltage from Figures 4 and 5.	19
8	Voltages at Which Current Declines Sharply, as a Function of Sequence in Test Series	20
9	Threshold Voltage for Pressure Surges as a Function of Gap Separation. (Treatment dg)	21
10	Relative Gas Evolution Rate as a Function of Gap Separation from Theoretical Model.	26
11	Variation of Gas Evolution Rate with Anode Power Dissipation from Theoretical Model.	27
12	Current Variation up to Breakdown at Different Gap Separations. (Test Sequence (1))	30

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
13	Current Variation up to Breakdown at Different Gap Separations. (Test Sequence (2))	31
14	Current Variation up to Breakdown at Different Gap Separations. (Test Sequence (3))	32

PURPOSE

The factors influencing breakdown in high voltage vacuum devices will be studied. The information obtained will provide the basis for improvement in the design of microwave and modulator tubes that must operate at voltages greater than 100 kilovolts without breakdown.

ABSTRACT

The pilot experiment has been continued and treatments 13 through 29 were completed. The procedures previously developed were used to obtain the significant breakdown parameters of unconditioned and conditioned gaps in the range 0.5 to 3.0 cm. Preliminary analyses both statistical and physical were carried out, some trends were observed and tentative conclusions were drawn as to the mechanism causing breakdown. Finally the 300 kv system has been maintained in a fully operational state.

LECTURES, CONFERENCES AND PUBLICATIONS

Lectures and Conferences

24 May 1966

The monthly meeting to review progress on the contract was held at IPC on 24 May. G. W. Taylor from Fort Monmouth attended. The results of the first fifteen completed treatments were discussed.

25 May 1966

A presentation was made to the Advisory Group on Electron Devices which held its monthly meeting at IPC on 25 May. A. S. Denholm, M. J. Mulcahy, G. K. Simcox, M. M. Thayer and A. Watson took part, and both the preliminary experiment, the 300 kv apparatus and progress in the designed experiments were discussed.

27 June 1966

The monthly meeting to review progress on the contract was held at IPC on Tuesday 27 June. M. M. Chrepta from Fort Monmouth attended. The results of the first 22 treatments were discussed, 16 of which had been submitted to preliminary analysis. The program schedule to completion was also discussed.

8 July 1966

Dr. H. Doolittle from Machlett Laboratories visited IPC on 8 July and the results of the designed experiment were discussed with him.

15 July 1966

J. Weinstein from Fort Monmouth visited IPC on 15 July to discuss the statistical analysis of the results.

4 August 1966

The monthly meeting to review progress on the contract was held at IPC on 4 August. G. Taylor from Fort Monmouth attended and the results of the first 27 completed treatments were discussed.

Publications

Two papers were accepted for presentation at the Second International Symposium on Insulation of High Voltages in Vacuum, to be held at M. I. T. on 7, 8 September 1966. The titles were:

PREBREAKDOWN PHENOMENA IN VACUUM GAPS
A. Watson, A.S. Denholm and M.J. Mulcahy
Ion Physics Corporation

DESIGNED EXPERIMENTS ON HIGH VOLTAGE VACUUM BREAKDOWN
M.J. Mulcahy, A.S. Denholm and A. Watson
Ion Physics Corporation
G. Taylor and M. Chrepta U. S. Army Electronics Command

1. INTRODUCTION

The work reported herein describes the seventh three months of a study of high voltage breakdown in vacuum with particular application to problems encountered in the development of high power vacuum tubes.

The objectives of this period were to maintain the 300 kv system in full operational state and to continue the pilot experiment.

1.1 300 kv System

Eight system and nine electrode bakeouts were carried out and thermocouple records indicate that satisfactory levels of temperature were attained. Selected high tensile bolts were replaced in rotation after each system bakeout. The high voltage bushing was assembled eight times without problems during the quarter and both the Van de Graaff high voltage generator and the monitoring apparatus have been maintained in a fully operational state. Finally, assembly and checkout of the magnetic field and energy storage systems has been initiated.

1.2 Pilot Experiment

The pilot experiment was continued and treatments 13 through 29 were carried out. For each treatment six gaps were examined in the range 0.5 to 3.0 cm and the procedures developed during the first 12 treatments yielded breakdown voltage and current data for unconditioned and conditioned electrodes at all gap spacings. The results have been analysed, both statistically and on the basis of the physical mechanisms involved and a tentative theory has been developed to explain the breakdown trends.

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2. 300 KV TEST VEHICLE

2.1 Vacuum Chamber

Eight systems and nine electrode bakeout cycles were completed during which no measureable chamber leaks developed. The bakeable feed-through valve was replaced during this period and likewise the bolts and the gold O-ring on the top plate of the bakeable column after each system bakeout.

The pressure in the chamber prior to initiation of each test was approximately low 10^{-7} to high 10^{-8} torr region for electrode only bakeout and low 10^{-8} torr region for full system bakeout. The Roots blower and the ion pump were both cleaned and overhauled during the period.

2.2 Baking System

Eight full system bakeouts have been successfully completed. The problem of severe outgassing above 200°C encountered in the previous quarter has been overcome by allowing the system to pump down for more than 24 hours before raising the temperature.

As reported in the previous Quarterly Progress Report, the full baking cycle takes about 48 hours. The heaters are energised for 16 hours and this means that the electrodes are at about 400°C for 12 hours. After completion of system or electrode only bakeout the electrodes were allowed to cool to less than 50°C before voltage application. Thermocouple problems were encountered with the high voltage electrode and these have precipitated a redesign of the feedthrough connections on top of the bakeable column of the bushing.

2.3 High Voltage Power Supply

The high voltage power supply has operated satisfactorily and has provided precise voltage control and regulation up to 300 kv with an available current of greater than 200μA. The screens and the belt in the generator have been replaced as also has the oil in which is housed the high voltage cable termination. It seems desireable to carry out the latter operation after every 16 treatments.

2.4 Monitoring and Recording

The monitoring and recording apparatus has functioned satisfactorily providing records of the following parameters during each treatment:

- total X-radiation
- collimated X-radiation
- light output
- partial pressure
- gap current

2.5 Magnetic Field System

The magnet coils are complete and final checkout of the power supplies has been initiated.

2.6 Energy Storage System

Assembly of the energy storage system is nearly completed and final design of the trigger circuit except the energy diverter has been started. It is hoped to check the system out initially using an air gap at atmospheric pressure.

2.7 Feedthrough Bushing

2.7.1 General

The feedthrough bushing was assembled eight times during the reporting period. Only minor problems of contact between the springs and the rings were encountered. In some cases, one or two springs were broken, but it is of interest to note that this did not apparently effect the performance of the bushing. It seems also that the bakeable column has become more conditioned, evidenced by the reduction in magnitude or complete lack of those pressure surges which were associated with gas release from the column.

2.7.2 Bakeable Column

The bakeable column has now undergone nineteen bakeouts which is in excess of most of the estimates of its lifetime in terms of heating cycles. Delivery of the second ceramic column from General Electric is scheduled for the end of August.

2.7.3 Unbakeable Column

The glass-aluminum vinyseal bonded structure has operated satisfactorily during the reporting period.

2.8 Dielectric Envelopes

Quotations for the ceramic cylinders have been recieved and are being evaluated.

2.9 Electrodes

Seventeen sets of electrodes were tested and examined during this reporting period. Photomicrographs were taken of electrode surface damage and as previously described,[1] all breakdown markings were categorized.

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3. PILOT EXPERIMENT

3.1 Introduction

In the reporting period treatments 13 through 29 were completed. The procedures detailed in the Sixth Quarterly Progress Report were followed for electrode preparation and installation, bakeout and voltage application and similarly yielded information for unconditioned and conditioned electrodes in the gap range 0.5 to 3.0 cm. For treatments 1 through 5 however, which were carried out in the previous reporting period isolated breakdowns were neglected and the repetitive breakdown voltage only was measured. From a physical analysis of the results obtained by these procedures a theory of the breakdown process was derived and compared with experimental data obtained at various stages of conditioning. The results were also subjected to statistical analysis and preliminary trends obtained.

3.2 Physical Analysis of Results

3.2.1 Procedures

The repetitive sparking technique yielded almost linear curves of breakdown voltage, V_B as a function of gap separation, $\underline{d}^{1/2}$ and the logarithm of the current immediately prior to breakdown had a corresponding negative linear dependence.

With the introduction of the isolated breakdown technique, however, neither the breakdown voltage nor the logarithm of the penultimate prebreakdown current were any longer linear functions of the square root of the gap separation. For this technique the voltage is removed after each breakdown. Both techniques yielded curves of V_B as a function of $\underline{d}$ at various stages of the conditioning process. The former technique however, by neglecting isolated sparks, achieved some conditioning at each gap separation. The isolated spark technique on the other hand more closely approximates the other limit of achieving no conditioning during a test. Thus it would be expected that if it were repeated after progressively greater numbers of sparks had occurred then the corresponding curves should tend towards those obtained by the repetitive sparking method.

3.2.2 Breakdown Voltage and Prebreakdown Current Data

During treatment abcefg (See Table 1) breakdown voltage and penultimate gap current were investigated as functions of gap separation as conditioning progressed (Figures 1-5). The isolated breakdown technique was employed, which is now standard procedure, and was repeated after two periods of 20 and 30 minutes of continuous sparking during each of which about 1000 sparks occured (Figure 1-3). This was followed by a two day rest and two more test series separated by 20 minutes sparking (Figures 4 and 5). During all of these

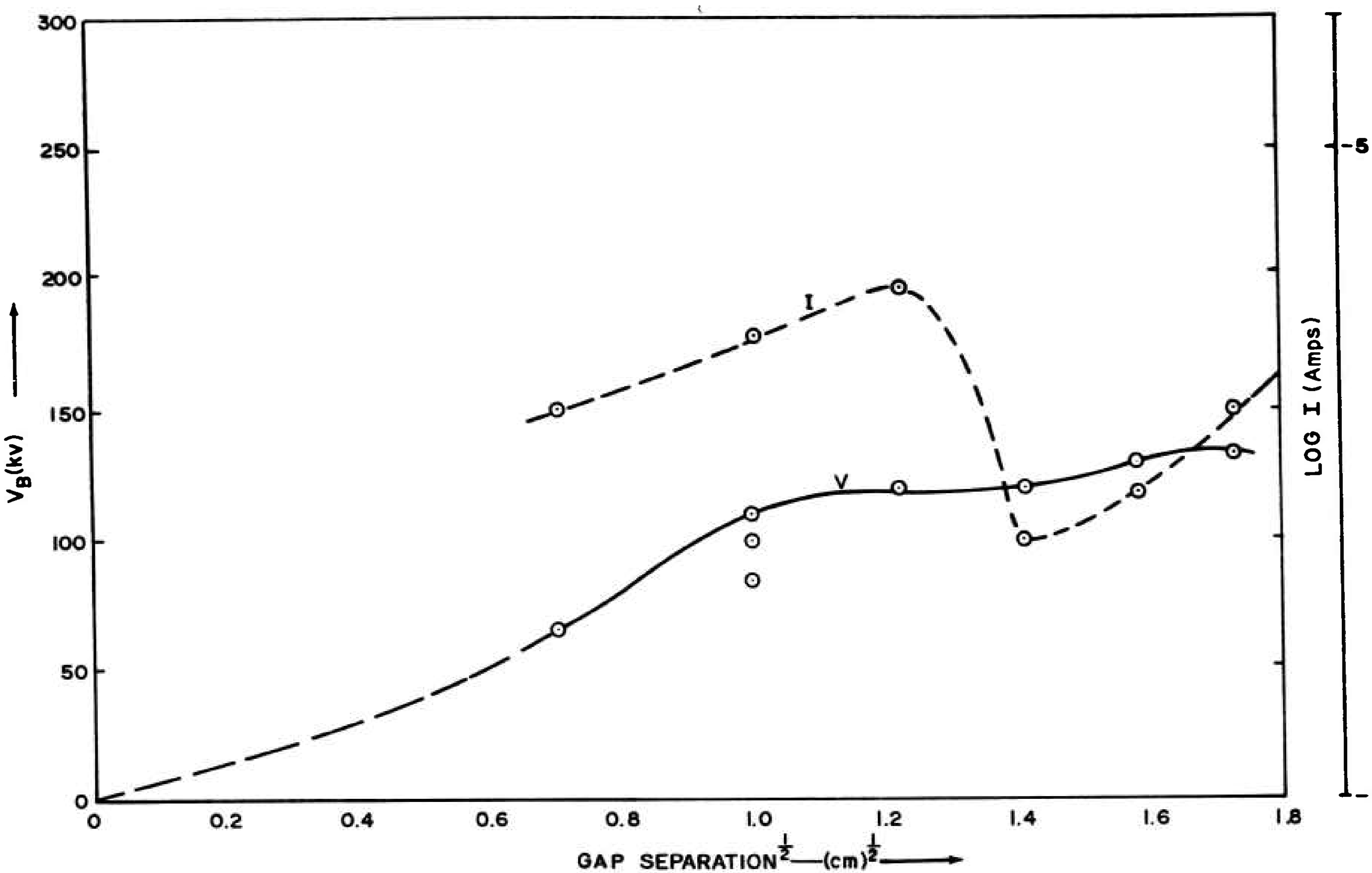

Figure 1. Breakdown Voltage and Penultimate Gap Current as Function of Gap Separation. Treatment abcefg Test Sequence (1) Fresh Electrodes.

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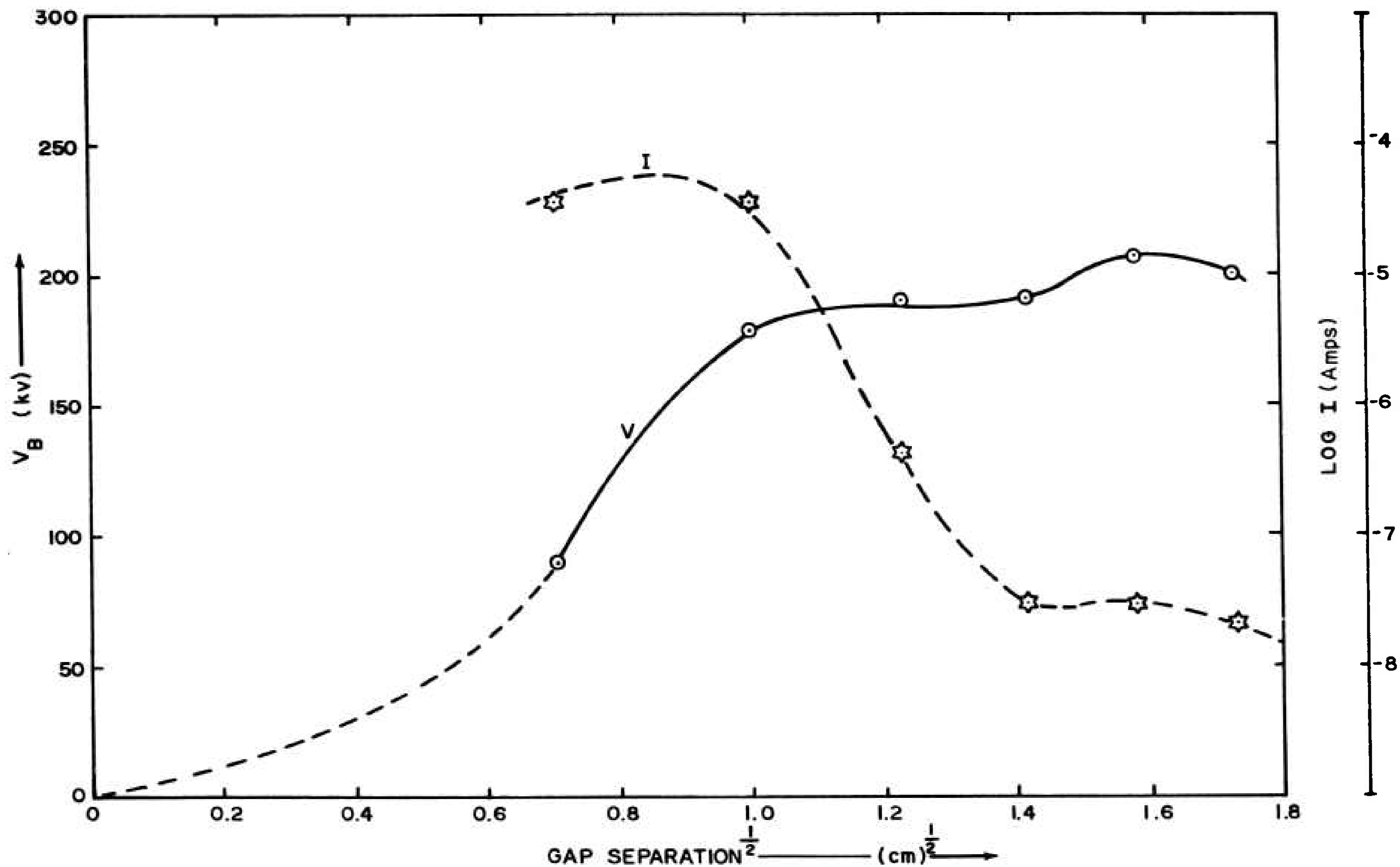

Figure 2. Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (2) after conditioning.

1-1767

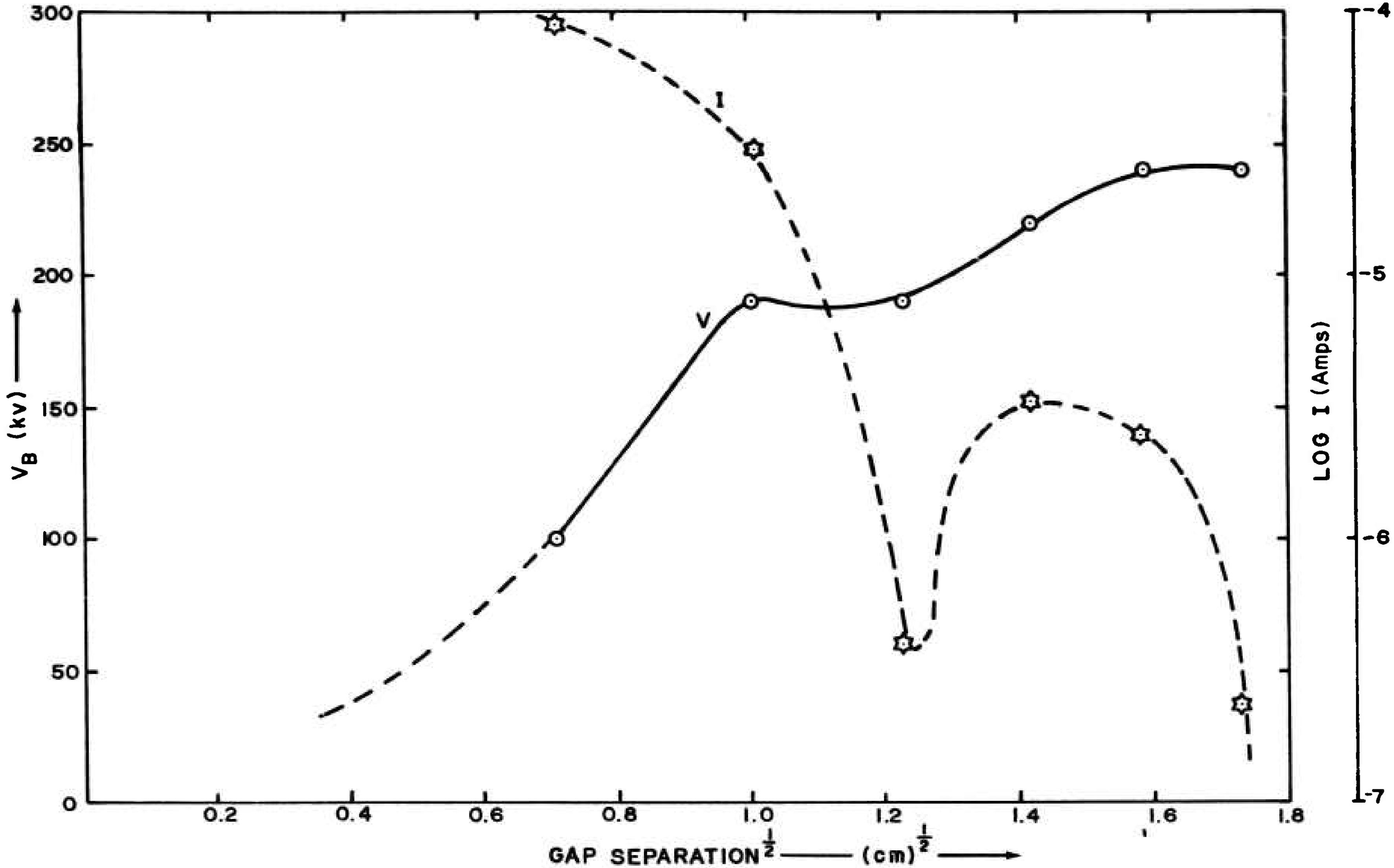

Figure 3. Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (3) after further conditioning.

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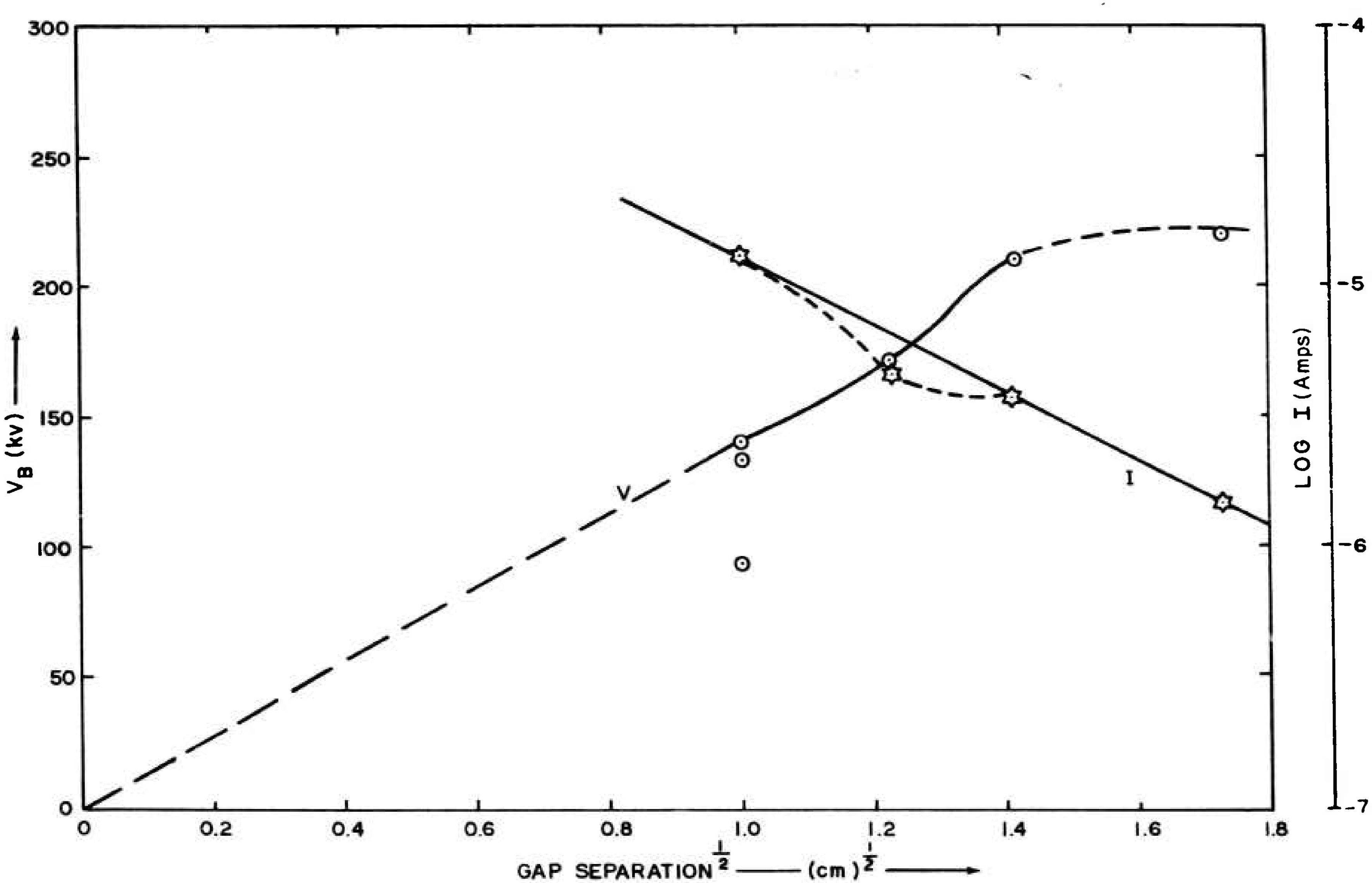

Figure 4. Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (4) after deconditioning.

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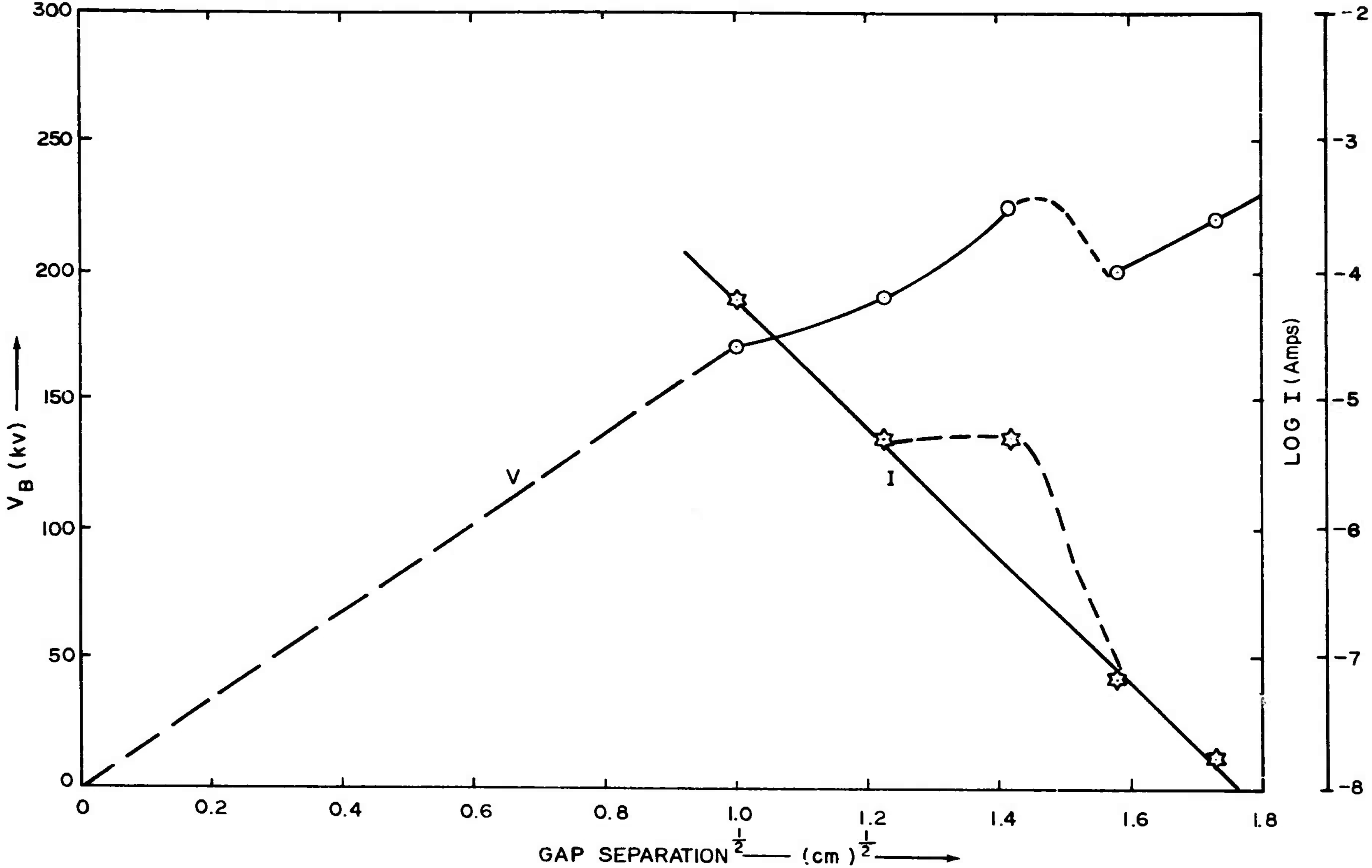

Figure 5. Breakdown Voltage and Penultimate Gap Current as Functions of Gap Separation. Treatment abcefg Test Sequence (5) conditioned after deconditioning.

1-1770

tests the prebreakdown gap current was recorded as a function of applied voltage and is presented in Figure 6 and 7 which shows a sharp decline in each case. Figure 8 shows the voltage at which this occurs as a function of the degree of conditioning.

3.2.3 Pressure Surges

During treatments following exclusively electrode bakeout, hydrogen pressure surges have been observed to precede gap failure at several kv below the breakdown voltage. These have been presented as a function of gap separation for treatment dg (Figure 9). In this particular treatment breakdown was accompanied by runaway in many cases. With copper electrodes particularly there is a tendency for microdischarges to take place during pressure surges.

During one treatment the mass spectrometer was tuned on to the nitrogen line. Several seconds after breakdown a very small response was observed as opposed to the release of hydrogen which occurs always previous to and during the breakdown.

3.3 Theory

3.3.1 Breakdown Mechanism

Examination of the results to date, as well as the experience gained from the preliminary experiment indicates that hydrogen gas evolution plays a significant part in the breakdown mechanism. To supplement this, a simple model of the breakdown mechanism has been conceived which, it is hoped, will provide a unified breakdown theory to explain the experimental data.

All breakdown mechanisms are characterised and can in fact be defined by the existence of a self regenerating process, such as an avalanche, which ultimately prevents the particular medium from supporting a strong applied electric field. In large vacuum gaps it is felt that the regenerative agent is hydrgen gas evolved from the anode.

Prebreakdown current impinges on the anode, producing a hot spot from which hydrogen is evolved into the inter-electrode space at a rate which is governed, among other things, by the amount of gas present near to the anode surface. The electron current producing this gas is emitted from a cathode site with a greatly enhanced field strength due to a localized projection which concentrates flux according to its geometry. In addition to this, however, there can be some field enhancement associated with ionization of evolved gas by the electron current. This ionization will be strongest close to the projection and the resultant current increase will raise the anode hot spot temperature, consequently releasing gas at a faster rate. Thus more ionization occurs and the process can be self regenerative until the transition to a vacuum arc is complete.

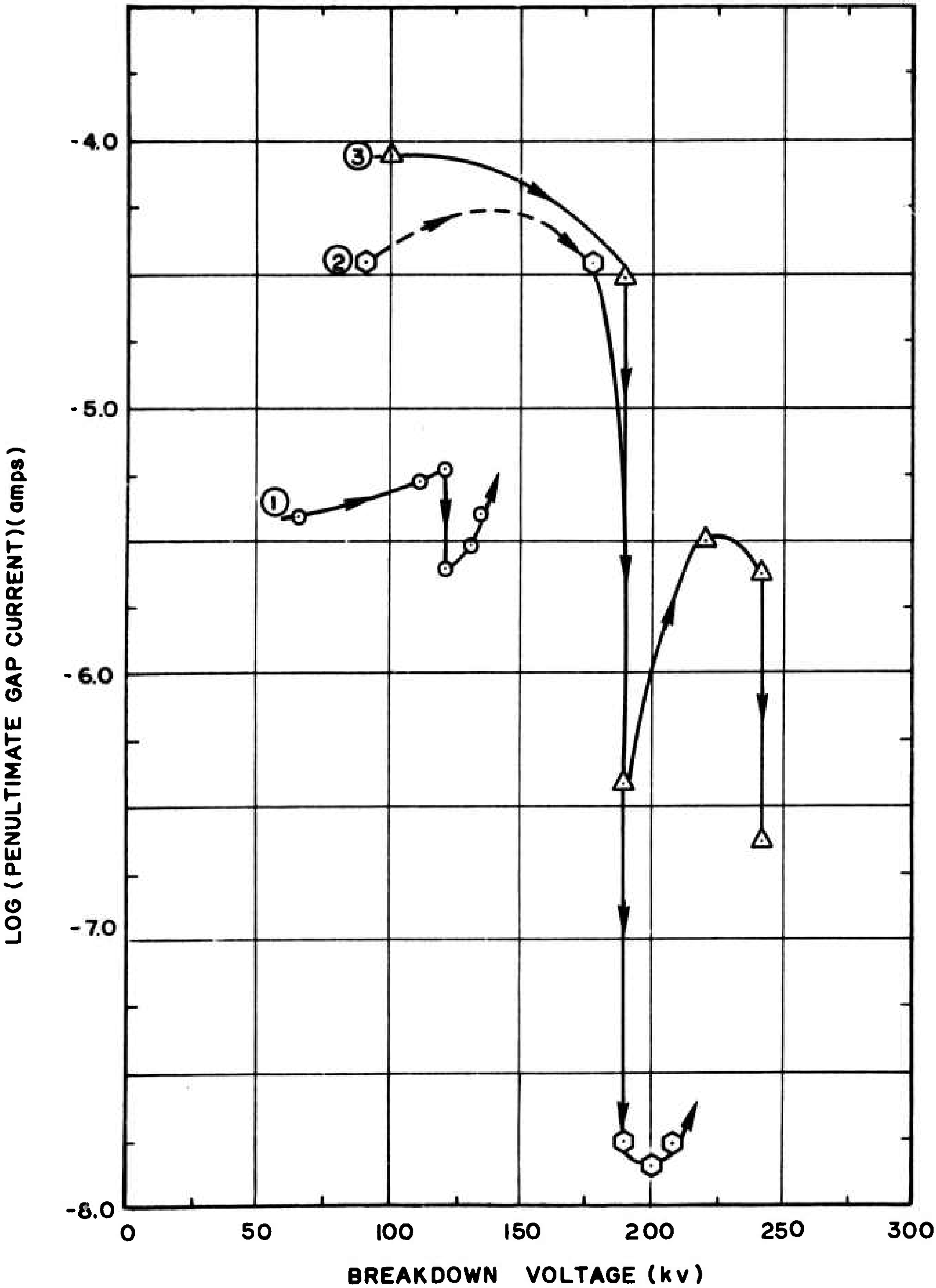

Figure 6. Penultimate Gap Current as a Function of Voltage from Figures 1-3.

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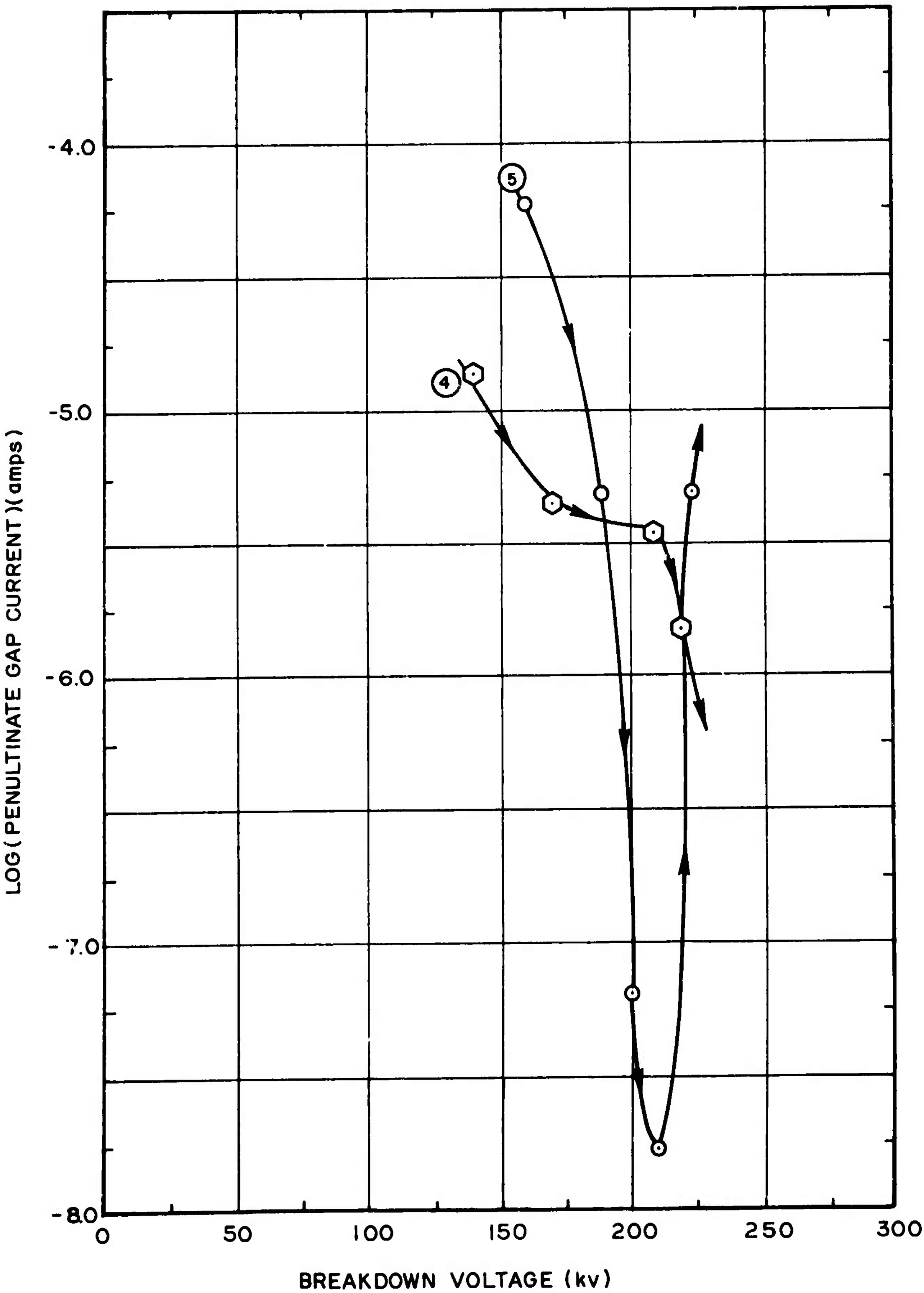

Figure 7. Penultimate Gap Current as a Function of Voltage from Figures 4 and 5

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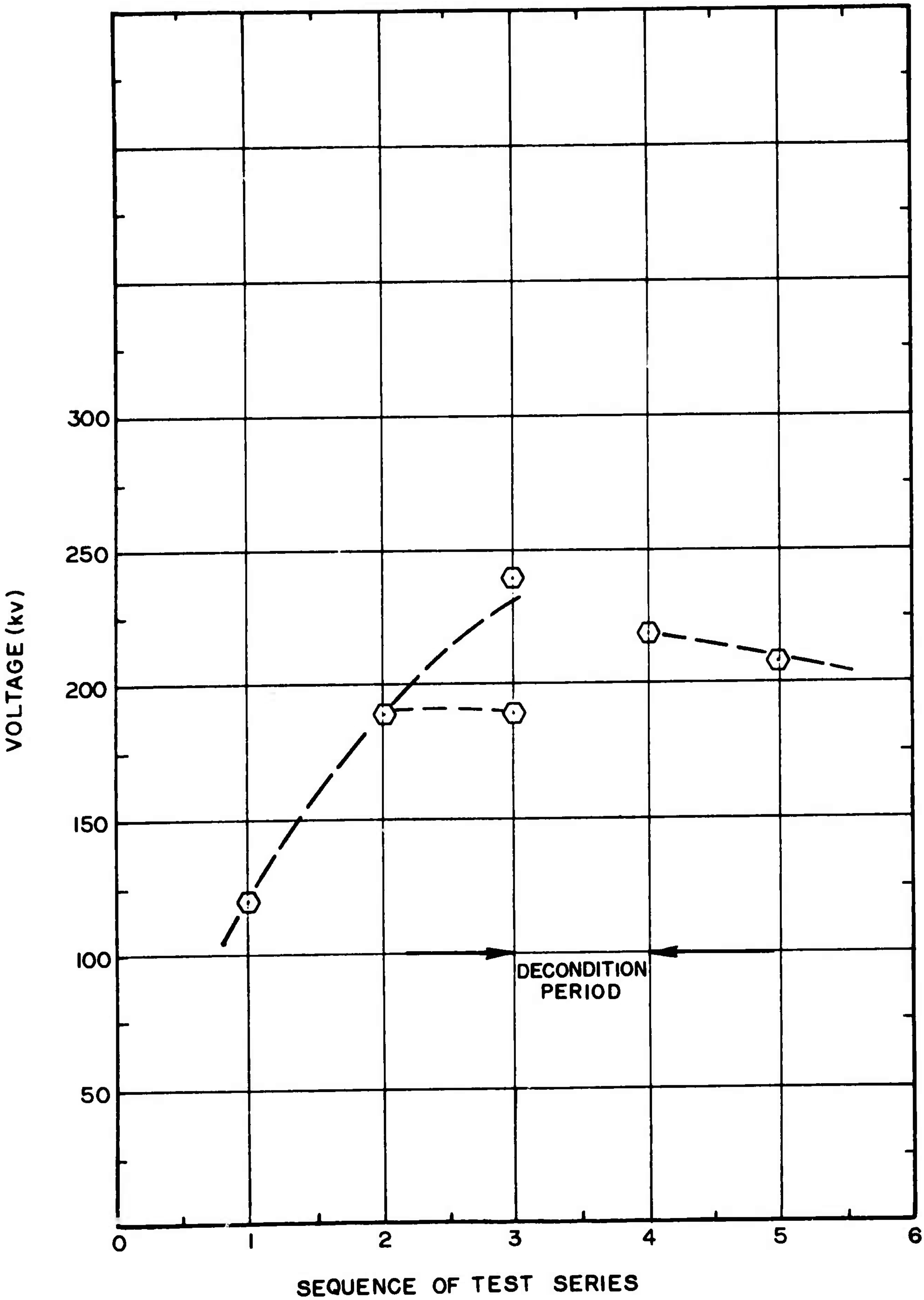

Figure 8. Voltage at which Current Declines Sharply, as a Function of Sequence in Test Series

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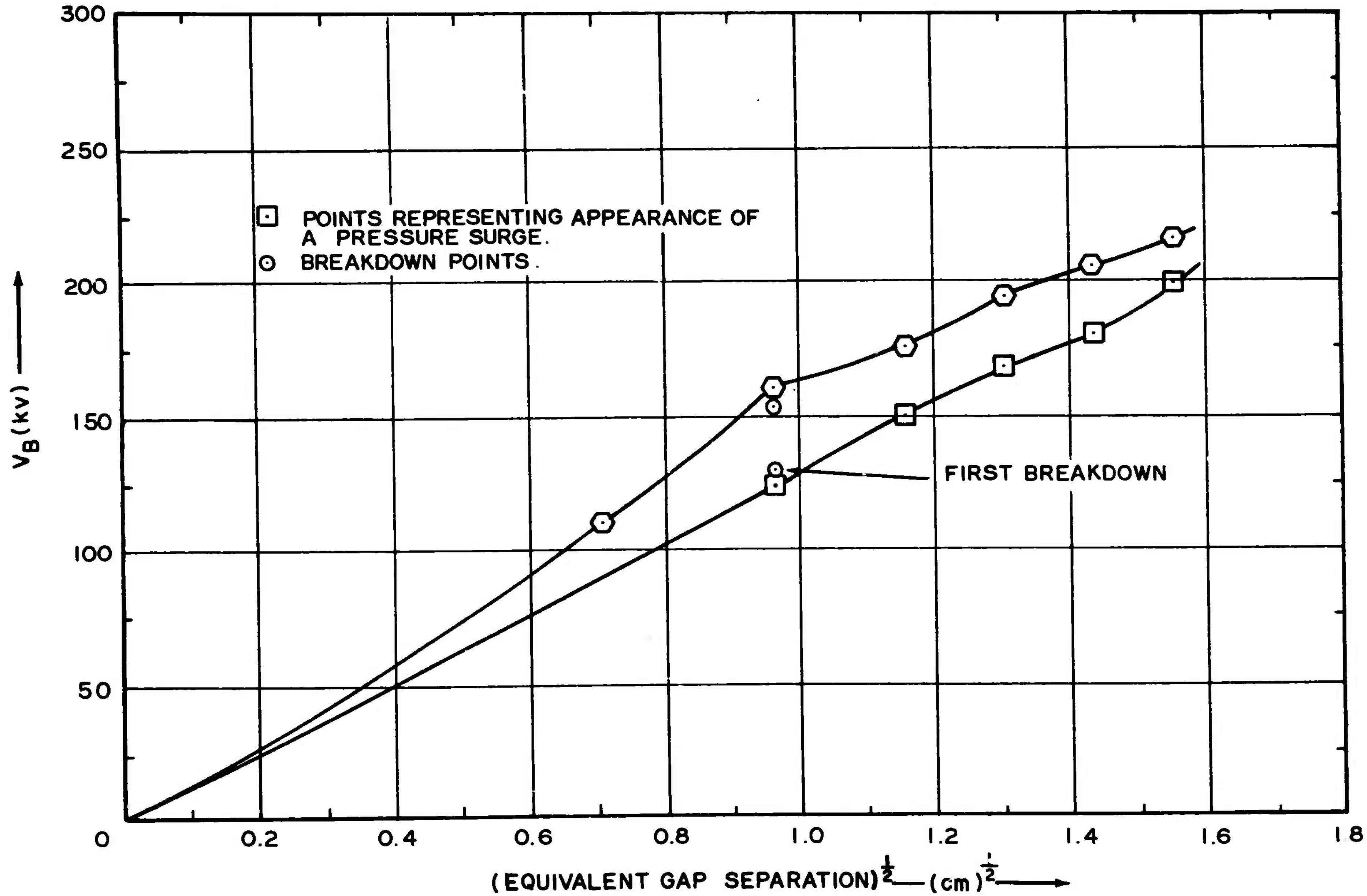

Figure 9. Threshold Voltage for Pressure Surges as a Function of Gap Separation (Treatment dg).

1-1774

This mechanism is consistent with the observation of runaway and it will be shown to explain prebreakdown current phenomena.

3.3.2 Field Enhancement

When field emitter tips are subjected to strong electric fields there is a gradient of chemical potential along the surface from regions of strong to weak curvature. Atoms migrate along the surface, partially correcting this gradient and establishing a distribution of curvature according to the local field strength. The rate of migration and the characteristic tip shapes have already been thoroughly investigated.[2] Experimental tip shapes have been shown to enhance the field at the tip in an almost inverse proportion to the local radius of curvature there. A good approximation has been given by Gomer[3] for the local tip field, E, in terms of the potential V, radius r and a constant, k.

$$E = \frac{V}{kr} \tag{1}$$

By definition:

$$E = \frac{\beta V}{d} \tag{2}$$

where β is the enhancement factor, d the gap separation, and V the applied voltage. Thus:

$$\beta = \frac{d}{kr} \tag{3}$$

At the same time the equilibrium tip radius has been shown[4] to be related approximately to the surface tension γ by the relation.

$$rE^2 = 12\pi\gamma \tag{4}$$

From Equations (2), (3) and (4) we have

$$\beta \frac{V^2}{d} = 12\pi\gamma k \tag{5}$$

If, however, E_s is supplemented by an ionic space charge field X_s, we have

$$E_s = \frac{V}{kr} + X_s \tag{6}$$

where E_s is the new total field strength at the tip. Hence Equation (5) would no longer be accurate. It might be surmised, however, that a highly conditioned system would have very little gas present and X_s would be small. In such a case Equation (5) would be approximately valid. A linear plot of V as a function of $d^{1/2}$ would then imply that breakdown takes place for some constant critical value of β. The non linearity of non conditioned plots would also follow readily by taking X_s into account. It should be emphasised that the possible existence of a constant critical field enhancement factor is not fundamental to the mechanism. The local surface field E_s is the critical factor and this is achieved by some value of β which governs X_s. In turn X_s is not achieved necessarily at the same value of β for all gap separations.

The development of the field emitted current and associated field enhancement induced by gaseous ionization willnow be discussed.

3.3.3 Field Emission Current

Since neither the field enhancement factor nor the area of emitting site remain constant as voltage is raised the gap current will not increase according to the Fowler-Nordheim expression. Current density will follow the Fowler-Nordheim relation, taking gaseous ionization into account by employing the total tip field strength E_s.

$$J_e = AE_s^2 \exp - \left(\frac{B}{E_s}\right) \tag{7}$$

and since $r E_s^2 = 12\pi \gamma$ we have

$$\begin{aligned} I_e &= \pi \, (1 + \cos \theta) \, r^2 \, J_e \\ &= \pi \left(\frac{12\pi\gamma}{E_s^2}\right)^2 (1 + \cos \theta) \; A E_s^{-2} \exp \left(-\frac{B}{E_s}\right) \end{aligned} \tag{8}$$

where θ is defined as the angle to the axis of the protrusion within which most of the electron current is confined and $\pi \; r^2 \; (1 + \cos \theta)$ is the effective area of the tip. Combining equations (4) and (8)

$$\left.\begin{aligned} I_e &= \alpha \, E_s^{-2} \exp - \left(\frac{B}{E_s}\right) \\ \alpha &\equiv \left[\pi \; A \, (1 + \cos \theta)\right] \; (12 \pi \gamma)^2 \end{aligned}\right\} \tag{9}$$

3.3.4 The Anode Temperature and Rate of Gas Evolution

After leaving the cathode the electron beam diverges to a radius R at the anode. Simple conductive heat transfer theory[5] shows that a beam power $I_e V$ will raise the hot spot to a temperature T above the ambient value T_a where T is the absolute temperature and

$$T - T_a = \frac{I_e V}{4KR} \tag{10}$$

where K = thermal conductivity of the anode. Gas will then diffuse from inside the anode at a rate depending upon the local value of the gas density gradient at the surface, $\left(\frac{dn}{dx}\right)_s$. Thus the rate at which gas approaches the surface is given by

$$\dot{n} = D \left(\frac{dn}{dx}\right)_s \tag{11}$$

and

$$D = D_o \exp\left(-\frac{h}{kT}\right) \tag{12}$$

where h is an activation energy. The number $\dot{N}$ of these crossing the unit area of the surface will depend on their surface "latent heat" h_s.

$$\dot{N} = \dot{n} \exp\left(-\frac{h_s}{kT}\right) \tag{13}$$

Thus

$$\dot{N} = D_o \left(\frac{dn}{dx}\right)_s \exp\left(-\frac{h + h_s}{kT}\right) \tag{14}$$

The value of $\dot{N}$ will fluctuate giving rise to current fluctuations. This is because in fact gas tends to be evolved in surges. The total rate of gas evolution will be proportional to the hot spot area πR^2. Hence

$$\dot{N} = \pi R^2 D_o \left(\frac{dn}{dx}\right)_s \exp\left(-\frac{h + h_s}{kT}\right) \tag{15}$$

To preserve analytical simplicity (although this may not always be justified) the approximation $T - T_a = T$ will be made. Hence from Equation (10) and (15)

$$\dot{N} = gR^2 \exp\left[-\frac{HR}{I_e V}\right] \tag{16}$$

where $g \equiv \pi D_o \left(\frac{dn}{dx} \right)_s$

and $H \equiv \frac{h + h_s}{k} \cdot 4K$

Chatterton[6] has obtained an expression for R in terms of r and $\sin\theta$. He finds:

$$R = 2d^{1/2} \quad \beta r^{1/2} \sin\theta \tag{17}$$

Hence from Equation (3) we have:

$$R = \lambda d \tag{18}$$

where $\lambda = 2k^{1/2} \sin\theta$

Hence:

$$\dot{N} = g\lambda^2 d^2 \exp\left(- \frac{H \lambda d}{I_e V} \right) \tag{19}$$

Curves are plotted in Figure 10 of $\dot{N}/g\lambda^2$ as a function of d for four arbitrary values of

$$w \equiv \frac{I_e V}{H\lambda} \; .$$

From these $\dot{N}$ is derived as a function of w at various values of d. (Figure 11) showing the manner in which the rate of gas evolution increases with prebreakdown power dissipation at various gap separations.

It remains now to describe the manner in which the cathode field is enhanced by the presence of gas.

3.3.5 The Ionic Space Charge Field

Close to the cathode projection there is a region of high ionization probability where the electrons have just been accelerated to about the ionization potential of the evolved gas. Between here and the cathode surface the ion current density J_+ and electron current density J_e generate a combined space charge field which has the value X_s on the cathode surface.[7]

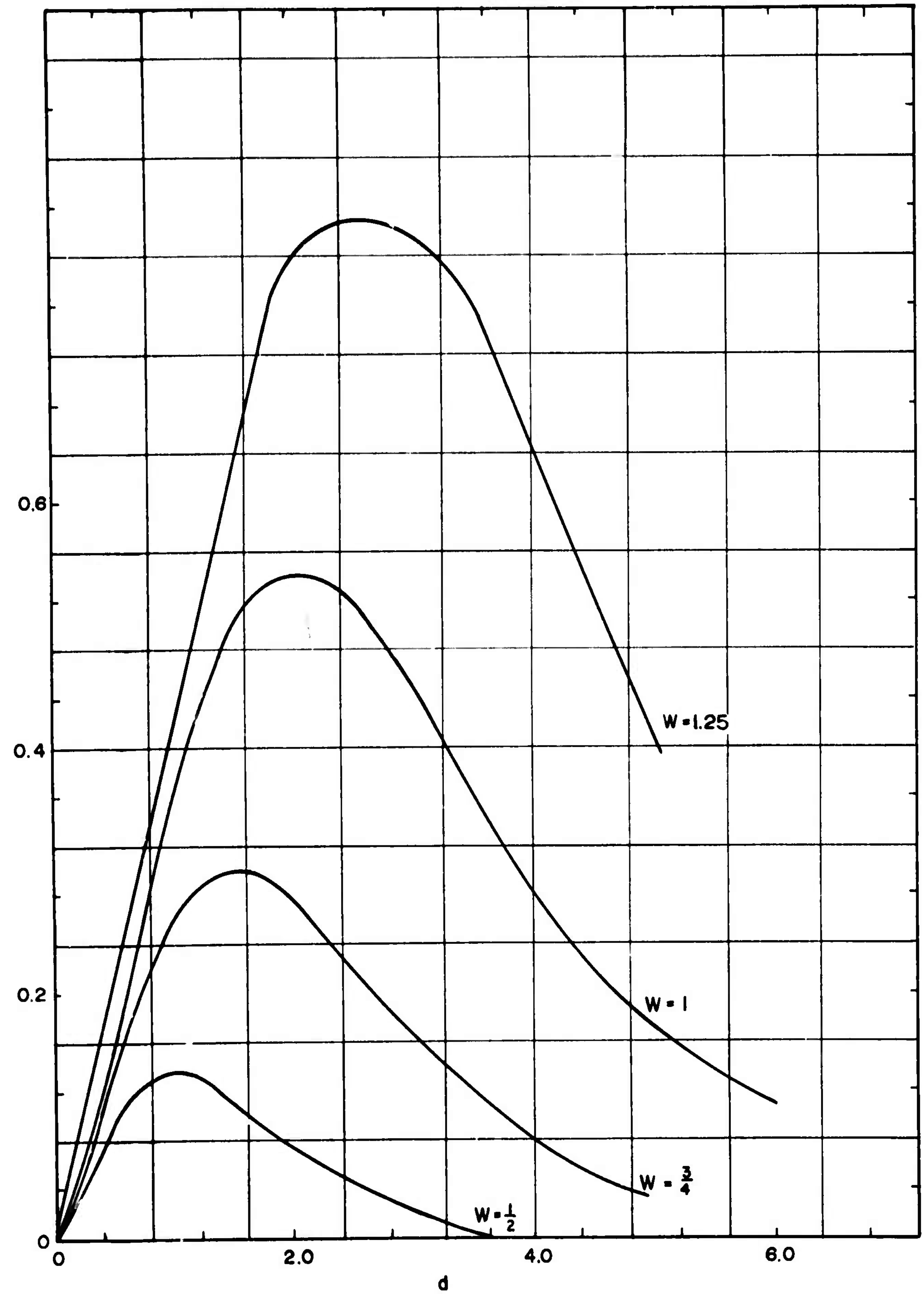

Figure 10. Relative Gas Evolution Rate as a Function of Gap Separation from Theoretical Model

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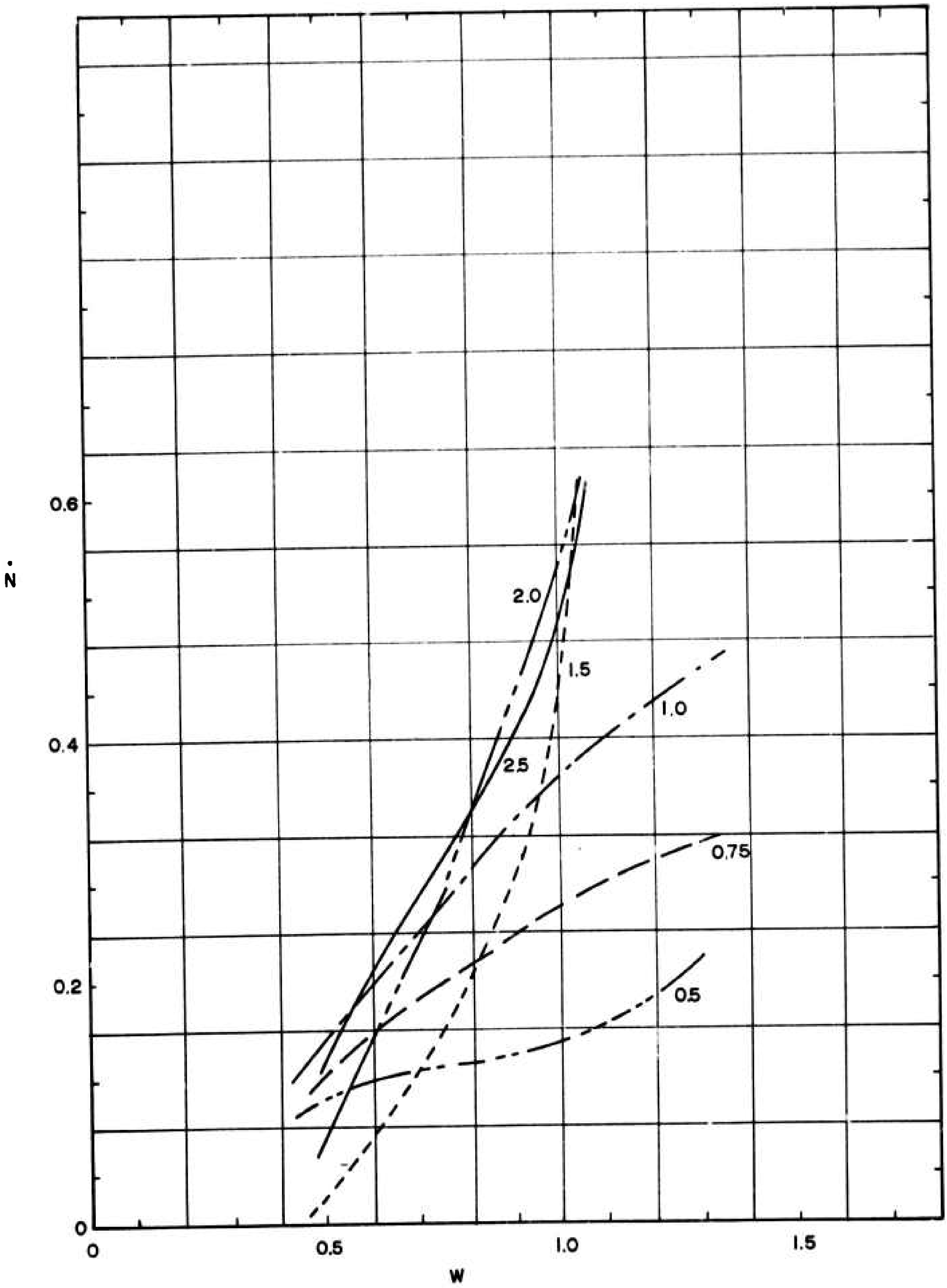

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Figure 11. Variation of Gas Evolution Rate with Anode Power Dissipation from Theoretical Model

$$X_s^2 = \phi J_e \left[\frac{J_+}{J_e} \sqrt{\frac{m_+}{m_e}} - 1 \right] \tag{20}$$

Where

$$\phi = \frac{16\pi}{\sqrt{\frac{2e}{m_e}}} \sqrt{U}$$

and U is the potential difference between the region of ion generation and the cathode surface i.e., U $\approx$ ionization potential of the gas. For hydrogen $m_+ = 1837\ m_e$ and so J_+ must be greater than $J_e/43$ to generate a field enhancement.

Gas will accumulate to a density N depending on $\dot{N}$ and the pumping conductance of the gas S which is considered independent of gap separation for analytical simplicity.

$$N = \frac{\dot{N}}{S} \tag{21}$$

Ions will be generated at the rate

$$J_+ = \dot{N}_+ = N J_e \frac{\sigma_i}{e} = \left(\frac{\sigma_i}{eS}\right) \cdot J_e \dot{N} \tag{22}$$

where σ_i is the cross section for ionization.

Thus

$$\frac{J_+}{J_e} = \left(\frac{\sigma_i}{eS}\right) \cdot \dot{N} \tag{23}$$

$$X_s^2 = \phi J_e \left[\left(\frac{\sigma_i}{eS} \sqrt{\frac{m_+}{m_e}}\right) \dot{N} - 1 \right] \tag{24}$$

Equation (24) can now be used together with Equation (6) to describe the manner in which the surface field E_s at the tip of the cathode protrusion varies with applied voltage. We have

$$E_s = \frac{V}{kr} + \left[\phi\, J_e \left[\left(\frac{\sigma_i}{eS} \sqrt{\frac{m_+}{m_e}} \right) \dot{N} - 1 \right] \right]^{1/2} \tag{25}$$

But

$$r\, E_s^{\;2} = 12\, \pi\, \gamma$$

and

$$J_e = \frac{I_e}{\pi\, r^2 (1 + \cos\theta)} \tag{26}$$

$$\therefore\ E_s = \frac{V}{12\,\pi\,\gamma k} E_s^{\;2} + \frac{E_s}{12\pi\gamma} \left[\frac{\phi}{\pi\,(1 + \cos\theta)}\, I_e \right.$$

$$\left. \times \left[\left(\frac{\sigma_i}{eS} \sqrt{\frac{m_+}{m_e}} \right) \dot{N} - 1 \right] \right]^{1/2}$$

$$\therefore\ \frac{VE_s}{k} = 12\,\pi\,\gamma - \left[\frac{\phi}{\pi\,(1 + \cos\theta)} I_e \left[\left(\frac{\sigma_i}{eS} \sqrt{\frac{m_+}{m_e}} \right) \dot{N} - 1 \right] \right]^{1/2} \tag{27}$$

Inspection of this shows that when $\dot{N}$ is low E_s is inversely proportional to V. At a sufficiently large value of V, both I_e and N become great enough to reduce the value on the right hand side of this equation and consequently E_s drops below the value $12\,\pi\,\gamma\ k/V$. The magnitude of the reduction will be greater for large values of I_e. Moreover, since N is proportional to $\left(\frac{dn}{dx}\right)_s$ then if this is low, a higher voltage V and surface field E_s will be required to generate a particular value of N. Thus at different stages of conditioning the voltage at which this phenomenon occurs should increase.

3.4 Interpretation of Results

Throughout the treatment abcefg, in which current was monitored as a function of voltage up to breakdown, the curves obtained (Figures 12 and 14) appeared concave to both the ordinate and abscissa axes. The shapes varied somewhat with gap separation and voltage and are strikingly similar to those of Figure 13 which displays the variation of gas evolution rate with increasing power dissipation. This occurs because of the role played by gaseous ionization in modulating the field enhancement at the cathode and hence the current from it.

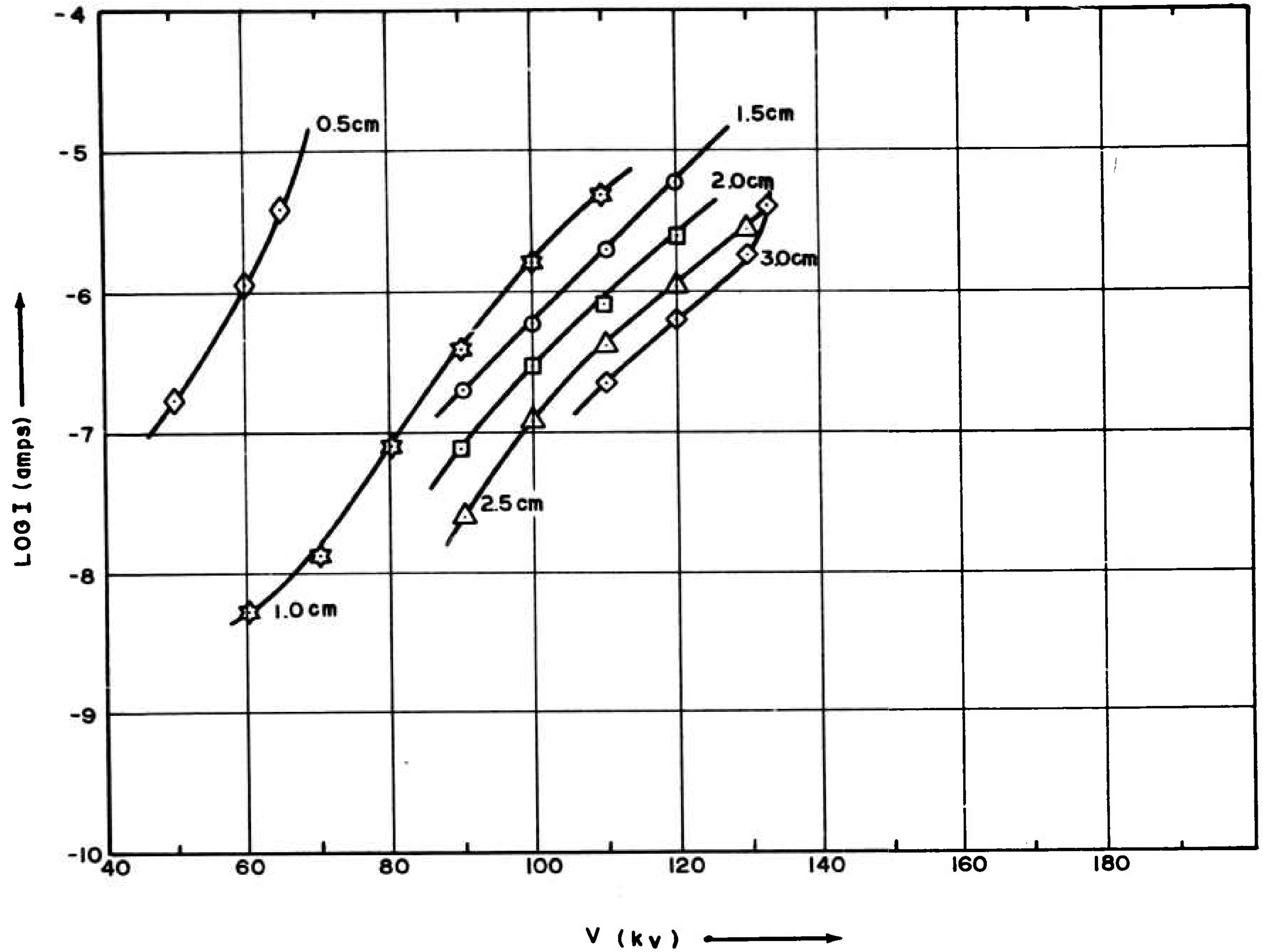

Figure 12. Current Variation up to Breakdown at Different Gap Separations. (Test Sequence (1))

1-1777

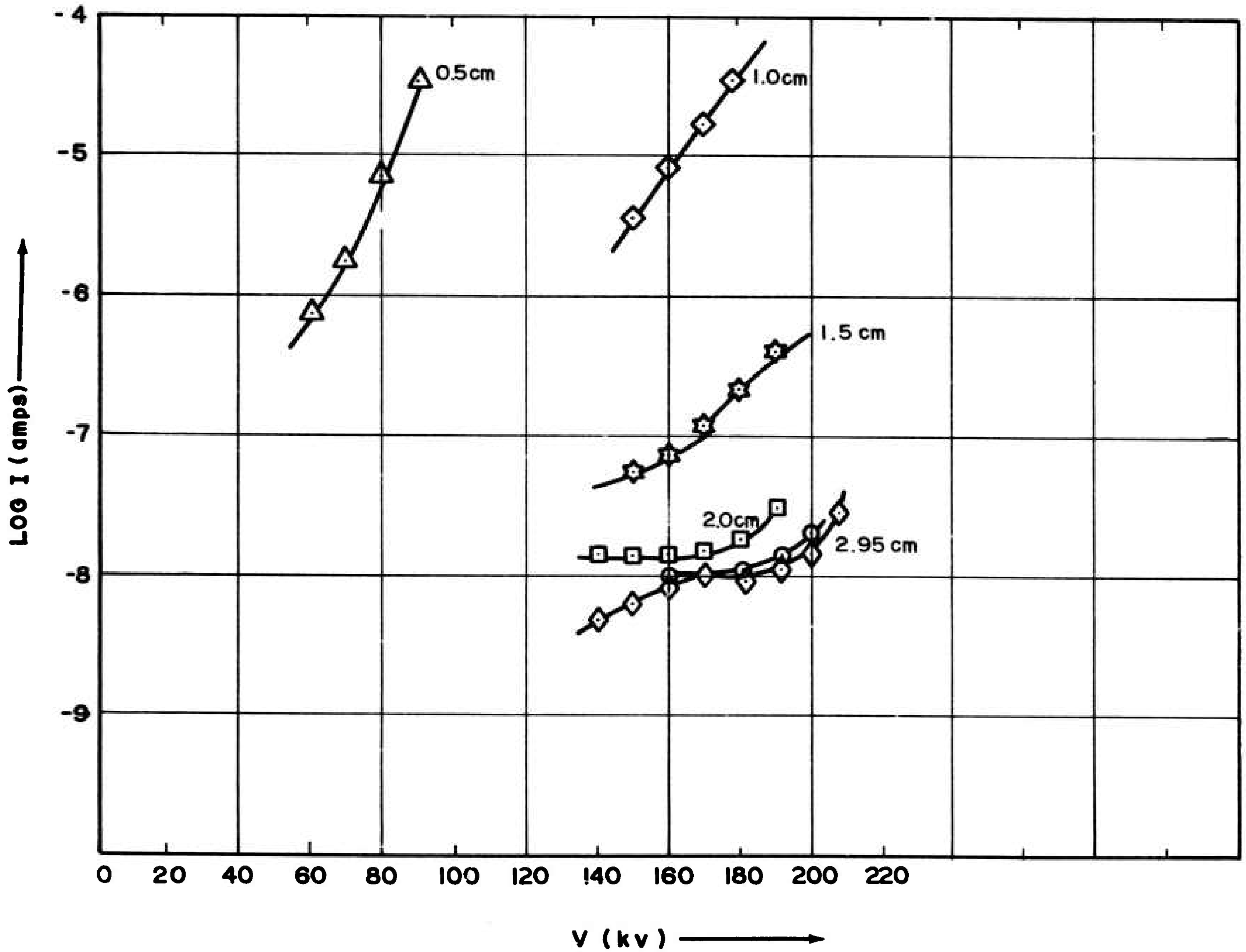

Figure 13. Current Variation up tc Breakdown at Different Gap Separations. (Test Sequence (2))

1-1778

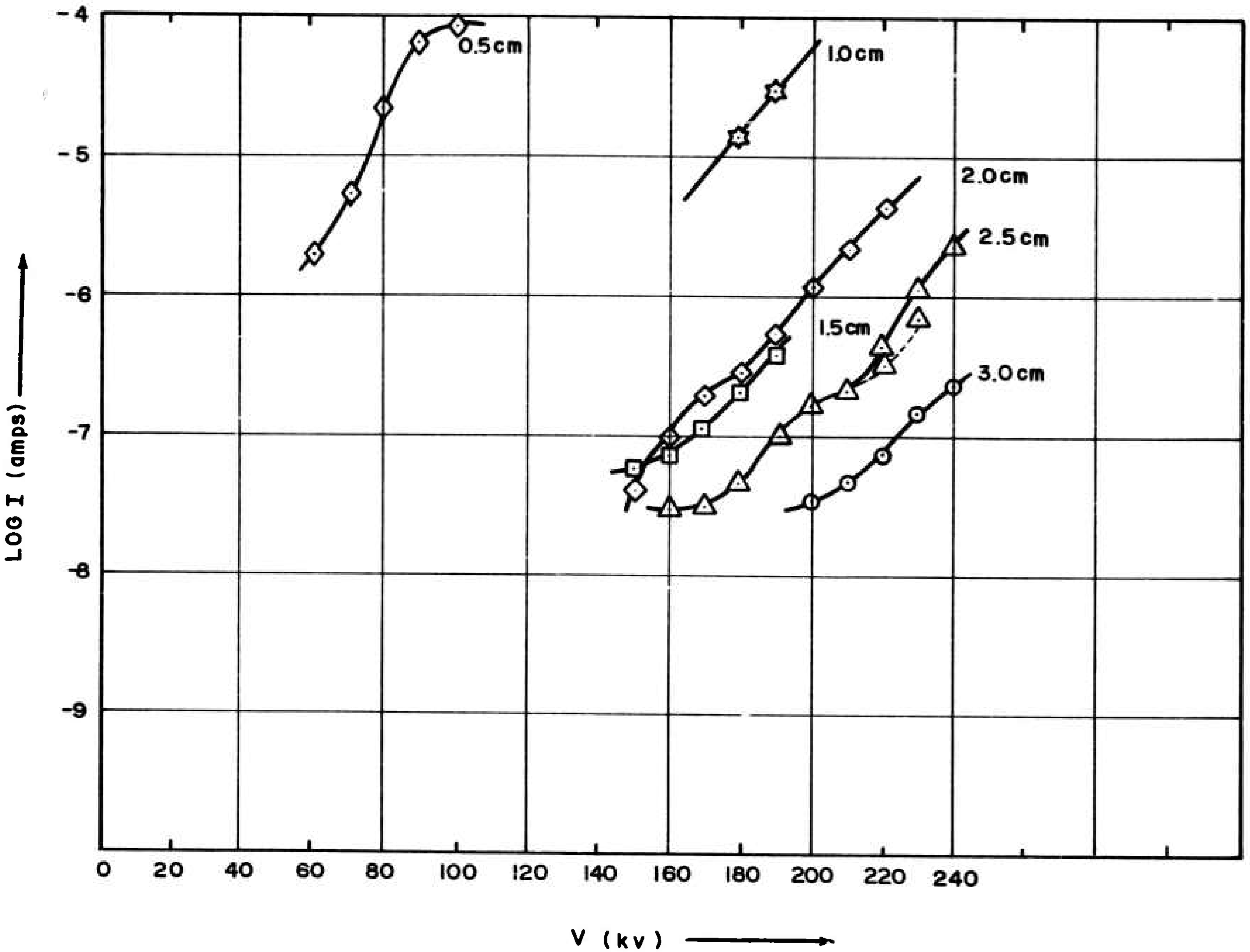

Figure 14. Current Variation up to Breakdown at Different Gap Separations. (Test Sequence (3))

1-1779

The penultimate gap current has been plotted as a function of the corresponding voltage (the breakdown value) in Figure (7). These graphs each show a sharp drop in current at a particular gap separation and voltage, the phenomenon following the theoretically predicted behavior described by Equation (27). The magnitude of the drop increases at high currents and another graph (Figure 8) has been drawn to show that the voltage at which it occurs apparently increases with the experimental sequence, i.e., with conditioning.

In conclusion it appears that there is some experimental support for the theory outlined. Analysis is continuing to describe the form of the breakdown voltage as a function of gap separation.

3.5 Statistical Analysis of Results

The unconditioned and conditioned breakdown values for the 1.0 cm gap have been used for the preliminary statistical analysis of treatments 5 through 28, i.e., 24 treatments: the other gaps will be examined at a later date. The factors and levels are shown in Table 1.

Before presenting the results of the analysis and discussing the trends, the objectives of the pilot experiment should be borne in mind. Apart from investigation of the effects of the seven factors, these were familiarization with the apparatus and with the statistical technique and finalization of a procedure which could be used for all future tests. In fact, the procedure described in this report was not finalized until after about 9 treatments has been completed. Within this frame of reference, the analysis to date has yielded the following:

(1) The trends for the unconditioned values are given in Table 2. Positive signs signify that the breakdown voltage is increased when the relevant factor or factors are at the higher level and decreased when they are at the lower level; negative signs signify the reverse. Thus, for example, examining shape factor B, when the cathode geometry is Bruce profile the voltage is reduced by 6.7 kv and increased by 6.7 kv when the cathode is a sphere. However, since the standard deviation is 6.7, there is a low level of confidence in the trends of Table 2 especially beyond the top four. An encouraging factor, however, is that this standard deviation has decreased from 7.4 for 22 treatments to the present value of 6.7 for 24 treatments.

(2) The trends for the conditioned breakdowns exhibit a wider scatter such that the level of confidence is zero, not a surprising result considering the almost inherent uncertainties of the conditioning process. For example, after conditioning material transfer has occurred; in some cases strong etches appeared which persisted, while in other cases no etches appeared or they quickly disappeared. This is being examined further with a view to standardizing the conditioning.

Table 1. Factors and Levels for Pilot Experiment

Factors	Letters	Levels
Cathode Material	C	1 - Ti-7 Al-4 Mo
		c - OFHC Cu
Cathode Finish	G	g - Fine
		1 - Coarse
Cathode Geometry	B	b - Bruce Profile
		1 - Sphere
Bakeout	D	1 - Complete System Bakeout
		d - Electrode Bakeout Only
Anode Material	A	1 - Ti-7 Al-4 Mo
		a - OFHC Cu
Anode Finish	F	f - Fine
		1 - Coarse
Anode Geometry	E	e - Bruce Profile
		1 - Sphere

Thus treatment abcefg is a test consisting of an OFHC anode in the shape of a Bruce Plane with a fine surface finish apposing an OFHC cathode, Bruce Plane with a fine finish. For this treatment the complete system is baked out.

Table 2. Trends for Unconditioned Breakdown Voltages of 1.0 cm Gaps (Treatments 5 through 28)

Factors	Trend
AE + BC	-9.0
D	+7.0
B	-6.7
BD	-6.6
E	-6.2
AB + CE	-5.3
AG	-4.4
AD	+4.1
CD	+3.8
DG	-3.7
C	+3.5
G	+3.4
EG	-3.4
BE + AC	+3.4
DE	+2.7
A	-2.5
EF	-2.2
F	+2.1
AF	-2.1
CF	+2.0
DF	+1.8
BG	-1.8
FG	+1.3
BF	-0.8
CG	-0.2

(3) There is a trend towards increasing breakdown voltage with run number, as though the apparatus and/or the electrodes are undergoing long-term conditioning. The slope of this trend curve for electrode only bakeout is three times that for system bakeout.

(4) There is indication that the history of the electrodes may have some significance. However, no conclusions are warranted as yet.

3.6 Conclusions

The main statistical conclusion to date is that the effect of no factor on simple combination of factors has proved strong enough to overcome the standard deviation or error function. This may be explained partly by the fact that the experiment is not yet complete and also by the fact that the procedure was not finalized until about 9 treatments has been completed. However, the possibility should not be ruled out that variations in the level of some uncontrolled factor may be responsible. Such a factor, for example, may be the bakeout temperature or the gas content of the electrodes. More meaningful conclusions will be drawn when the pilot experiment has been completed and the earlier treatments repeated.

Meanwhile, even these preliminary treatments have been of great value in that they have highlighted the need for controlled experimentation in vacuum breakdown to get meaningful results, and also the danger of drawing unwarranted conclusions from insufficient data. Several parts of this experiment, if conducted in isolation, could easily have led to conclusions which are shown to be unwarranted by the total experiment to date.

4. REFERENCES

(1) "High Voltage Breakdown Study", 6th Quarterly Progress Report, 16 May through 15 August 1966, Contract DA-28-043-AMC-00394(E).

(2) Dyke, W. P. and Dolan, W. W., "Field Emission", Advances in Electronics and Electron Physics, Vol. (8).

(3) Gomer, R. "Field Emission and Field Ionization", Chapter 2.

(4) Charbonnier, F. M., Martin, E. E., Strayer, R. W. and Bennette, C. J. Int. Symp. on Insulation of High Voltages in Vacuum, Oct. 1964.

(5) Carslaw, H. S. and Jaeger, J. C. "Conduction of Heat in Solids", 2nd Oxford (1959) p. 214.

(6) Chatterton, P. A., Proc. Phys. Soc., 88, 231 (1966).

(7) McKeown, S. S., Phys. Rev., 34, 611 (1929).

5. FUTURE EFFORT

During the next quarter the following will be pursued:

- The pilot experiment will be continued.
- The results will be tabulated and analyzed.
- Electrodes will be prepared, examined and photographed.
- The 300 kv system will be maintained in an operational state.
- The magnetic field system will be checked out.
- Final design and assembly of the energy storage system will be initiated.
- Dielectric cylinders will be prepared for test.

6. IDENTIFICATION OF PERSONNEL

The following personnel were active in the program during the period under review:

A. S. Denholm	-Department Manager
M. J. Mulcahy	-Project Manager
A. C. Stewart	-Engineering Manager
R. White	-Electrical Engineer
G. K. Simcox	-Electrical Engineer
M. M. Thayer	-Metallurgist
A. Watson	-Physicist
R. M. Parsons	-Engineering Aide
R. Benoit	-Design Engineer
C. Boudreau	-Engineering Aide
L. Indingaro	-Metallurgical Technician
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Prof. A. Argon	-Consultant MIT, Department of Mechanical Engineering
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13. ABSTRACT

The pilot experiment has been continued and treatments 13 through 29 were completed. The procedures previously developed were used to obtain the significant breakdown parameters of unconditioned and conditioned gaps in the range 0.5 to 3.0 cm. Preliminary analyses both statistical and physical were carried out, some trends were observed and tentative conclusions were drawn as to the mechanism causing breakdown. Finally the 300 kv system has been maintained in a fully operational state.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Electrical Breakdown in Vacuum						
Conditioning Procedures						
Optical and X-Radiation						
Partial Pressure and Gap Current						
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